

Method and Apparatus for Measuring Attitude

FIELD OF INVENTION

The present invention relates to the field of sensors. In particular, the
5 invention relates to a method and apparatus for sensing attitude in relation to
navigation systems and the like. In one form, the invention relates to a method
and apparatus providing a combination of gyroscopic and magnetometric
measurement for attitude sensing. It will be convenient to hereinafter describe
the invention in relation to the use of a gyroscope and a magnetometer to provide
10 attitude sensing for example in aircraft, however it should be appreciated that the
present invention is not limited to that use, only.

BACKGROUND OF THE INVENTION

Conventional attitude sensors include magnetic compasses and gyro
15 compasses. Many magnetic compasses utilize the earth's magnetic field and a
2-dimensional magnetic sensor to measure the azimuth angle in the horizontal
plane. A drawback of this known art is that they cannot provide accurate
measurement of azimuth in the case of non-zero pitch and roll angles. More
accurate magnetic sensors comprise a 3-axis magnetic sensor to measure the 3-
20 dimensional earth's magnetic field and a set of tilt sensors to measure the pitch
and roll angles. The tilt sensors may be electrolyte tilt sensors or may be made
up of accelerometers to measure the gravity vector. However, both types of tilt
sensors are subject to large errors in case of transitions of motions. Moreover,
the compasses using electrolyte tilt sensors also have inherent limitations such
25 as the slosh effect and large lag.

Conventional gyro compasses use gimballed gyroscopes to provide
attitude information with respect to a static coordinate system. The drawbacks of

conventional gyro compasses include the complexity of gimbaled systems, large size and high cost.

Rate gyros have been used together with other sensors to provide angular information. The inertial measurement unit (IMU) may comprise 3 orthogonally mounted accelerometers and 3 orthogonally mounted gyros to provide 3-dimensional acceleration and angular rate measurements. These measurements may then be used to generate 3-dimensional position, velocity and attitude information through inertial navigation processing. However, the accuracy of the attitude information will degrade with time due to the drift, scale factors and other error sources of the gyros and accelerometers. Magnetic sensors have been combined with rate gyros and other sensors to improve the accuracy. Examples are in US Patent No 5,645,077 to Foxlin. In US Patent No 6,480,152 to Lin an earth magnetic field detector is mixed with a GPS (Global Positioning System) and IMU to provide accurate position, velocity and attitude information. In these methods, the magnetic measurements together with the pitch and roll estimates provided by the inertial sensors are processed to generate the yaw angle. Then, this yaw angle is fed to a sensor fusion filter to generate compensation parameters. The inventor has identified that such methods neglect an important feature of the earth magnetic field, i.e., the vertical magnetic field intensity is almost invariant. This is shown in that only the magnetic sensor generated yaw angle is fed into the sensor fusion filter, but not the vertical magnetic field intensity and this may result in relatively larger attitude estimation errors. The inventor has also identified the following limitations. The magnetic compasses that utilize the earth's magnetic field and a 2-dimensional magnetic sensor to measure the azimuth angle in the horizontal plane, may have the drawback that they cannot provide accurate or even correct azimuth in case of non-zero pitch and roll angles. Both types of tilt sensors may be subject to large errors in case of transitions of motions. Also, compasses using electrolyte tilt sensors may have inherent limitations such as the slosh effect and large lag. Overall, the

inventor has identified that conventional gyro compasses may include the complexity of a gimbaled system, large size, and high cost.

Any discussion of documents, devices, acts or knowledge in this specification is included to explain the context of the invention. It should not be
5 taken as an admission that any of the material forms a part of the prior art base or the common general knowledge in the relevant art in Singapore or elsewhere on or before the priority date of the disclosure and claims herein.

An object of the present invention is to provide accurate attitude estimates in a useful and convenient form.

10 A further object of the present invention is to alleviate at least one disadvantage that may be associated with the prior art.

SUMMARY OF THE INVENTION

The present invention provides a method of determining an estimate of
15 attitude with respect to a fixed reference frame, the method comprising the steps of:

generating angles estimates comprising at least a pitch angle estimate, a roll angle estimate and a yaw angle estimate from measurements of a gyroscopic sensor means;

20 calculating a heading estimate from data comprising measurements of a magnetic sensor means and the pitch and roll angle estimates generated by the gyroscopic sensor means, and;

estimating signal parameters of the generated angle estimates from data comprising:

25 a) a difference of the calculated heading estimate based on the measurements of the magnetic sensor means and the heading estimate based on the measurements of the gyroscopic sensor means, and;

b) a difference of an estimate of the vertical magnetic field intensity based on measurements of the magnetic sensor means and an estimated true vertical magnetic field intensity.

Preferably, the estimated true vertical magnetic field intensity is derived
5 from an initialization module.

Preferably, the step of estimating may further comprise estimating signal parameters of the calculated heading.

The heading estimate may comprise one of an azimuth estimate, or a yaw angle estimate.

10 In a preferred embodiment, the method further comprises the step of compensating one or more of:

- a) the generated angle estimates; and
 - b) the calculated heading estimate
- with the estimated signal parameters.

15 Further the estimated signal parameters may comprise error parameter estimates of the measurements from the gyroscopic sensor means and the magnetic sensor means. The generated angle estimates may comprise a roll angle estimate, a pitch angle estimate and a yaw angle estimate. The calculated heading estimate based on magnetic sensor means comprises a calculated yaw
20 angle.

In a preferred embodiment, the step of estimating signal parameters comprises performing a Kalman filter operation on a numerical difference signal of the calculated heading estimate based on magnetic sensor measurements and the generated heading estimate based on gyroscopic sensor measurements.
25 Alternatively, an information filter may be used to perform this step.

In another aspect the invention provides apparatus adapted to determine an estimate of attitude with respect to a fixed reference frame, said apparatus including:

processor means adapted to operate in accordance with a predetermined instruction set,

said apparatus, in conjunction with said instruction set, being adapted to perform the method as disclosed herein.

5 In yet another aspect the invention provides a computer program product including:

a computer usable medium having computer readable program code and computer readable system code embodied on said medium for determining an estimate of attitude with respect to a fixed reference frame within a data processing system, said computer program product including:

10 computer readable code within said computer usable medium for performing the method as disclosed herein

The present invention relates to the method and in its embodiments to the use of 3-dimensional attitude sensors by combining gyros and magnetometers that can measure the 3-dimensional angular rate and the 3-dimensional earth's magnetic field.

15 The proposed method and apparatus makes use of the earth magnetic information and improves attitude accuracy.

Other aspects and preferred aspects are disclosed in the specification and/or defined in the appended claims, forming a part of the description of the invention.

In essence, the present invention stems from the realization that use of a vertical magnetic field estimate for attitude determination provides a greater level of accuracy and error control in particular in combination with gyro and magnetic measurements.

25 The present invention has been found to result in a number of advantages, such as for example the following.

1. High accuracy. The proposed method of integrating gyros and magnetic sensors will improve the attitude accuracy of the 3-

dimensional attitude apparatus compared to gyro only or magnetic sensor only attitude sensors.

2. Self-contained. The subject apparatus does not need external aids or to send out signals to the external world in order to obtain the attitude information of the carrier.

3. Fast response compared to magnetic compasses.

With the development of the MEMS technology, MEMS rate gyros have been developed and used in various applications. The availability of MEMS gyros can ensure that the present invention will have the following advantages:

4. Compact in size.

5. Low power consumption.

6. Solid state. The present apparatus does not contain moving parts that makes the system simpler to develop and more reliable.

7. Low-cost.

Further scope of applicability of the present invention will become apparent from the detailed description given hereinafter. However, it should be understood that the detailed description and specific examples, while indicating preferred embodiments of the invention, are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

Further disclosure, objects, advantages and aspects of the present application may be better understood by those skilled in the relevant art by reference to the following description of preferred embodiments taken in conjunction with the accompanying drawings, which are given by way of illustration only, and thus are not limitative of the present invention, and in which:

Figure 1 is a functional block diagram of a combinational gyroscopic and magnetic sensor integrated in accordance with an embodiment of the present invention wherein the heading is with respect to the magnetic north.

Figure 2 is a block diagram of a 3-dimensional attitude sensor system that
5 makes use of a combination of gyroscopic and magnetic sensing in accordance with an embodiment of the present invention.

Figure 3 is functional block diagram of an architecture for a 3-axis magnetometer and 3-axis gyroscope combination in accordance with another embodiment of the present invention wherein the heading is determined with
10 respect to true north, or geographic north as opposed to magnetic north.

Figure 4 is a functional block diagram of an architecture for a 3-axis magnetometer and 3-axis gyroscope combination in accordance with yet a further embodiment of the present invention wherein the heading is determined with respect to true north, or geographic north as opposed to magnetic north.

15

DETAILED DESCRIPTION OF THE INVENTION

With reference to figure 1 there is shown a block diagram of the processing modules for a combination of gyroscopic and magnetic sensors in put to determine attitude estimates in accordance with an embodiment of the
20 invention. In general, an integrated gyro/magnetic sensor or gyro/magnetometer are used to combine raw measurements from a 3-axis rate gyro and a 3-axis magnetic sensor to improve the accuracy of an estimated 3-dimensional attitude information compared to conventional magnetic compasses. Further, embodiments of the invention reduce the size, power consumption, and cost
25 compared to conventional gyro compasses. This method and apparatus also improves the attitude accuracy compared to previous integrated systems that may use gyros and magnetic sensors.

Background to Operation of Magnetic Sensors (Magnetometers) for Attitude Sensing

The earth's magnetic field intensity is about 0.5 to 0.6 gauss and has a component parallel to the earth's surface that always points toward magnetic north. This is the basis for all magnetic compasses.

The 3-axis magnetometer measurement vector may be defined as

$\bar{m} = [m_x \quad m_y \quad m_z]^T$ and the pitch and roll angles as θ and ϕ , respectively.

Denote the magnetic field intensity in the horizontal coordinate system as $\bar{H}_m = [H_x \quad H_y \quad H_z]^T$ which can be written as

$$\begin{aligned} \bar{H}_m &= \begin{bmatrix} H_x \\ H_y \\ H_z \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \sin \phi & \sin \theta \cos \phi \\ 0 & \cos \phi & -\sin \phi \\ -\sin \theta & \cos \theta \sin \phi & \cos \theta \cos \phi \end{bmatrix} \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} \\ &= \begin{bmatrix} m_x \cos \theta + m_y \sin \theta \sin \phi + m_z \sin \theta \cos \phi \\ m_y \cos \phi - m_z \sin \phi \\ -m_x \sin \theta + m_y \cos \theta \sin \phi + m_z \cos \theta \cos \phi \end{bmatrix} \end{aligned}$$

The azimuth with respect to the magnetic north can be calculated by

$$\psi_m = \arctan\left(\frac{H_y}{H_x}\right)$$

The earth's magnetic poles and its axis of rotation are not at the same geographical location. They are about 11.5° rotation from each other. This creates a difference between the true north, or grid north, and the magnetic north, or direction a magnetic compass will point. To account for the variation simply add, if Westerly, or subtract, if Easterly, the variation angle from the corrected heading computation. The variation angles have been mapped over the entire globe. For a given location the variation angle can be found using a geomagnetic declination map or a GPS reading and an IGRF model (International Geomagnetic Reference Field). The heading, or the azimuth, or the yaw angle with respect to the true north can be written as

$$\psi_m = \arctan\left(\frac{H_y}{H_x}\right) + \psi_v$$

with ψ_v representing the variation angle.

Error Models of Magnetometers

If the roll and pitch angles to resolve the magnetic measurements have errors, heading errors will be induced. Denote the estimated heading as

$$\hat{\psi}_m = \psi + \delta\psi_m = \arctan\left(\frac{\hat{H}_y}{\hat{H}_x}\right) + \psi_v$$

where

$$\begin{aligned}\hat{H}_x &= \tilde{m}_x \cos \hat{\theta} + \tilde{m}_y \sin \hat{\theta} \sin \hat{\phi} + \tilde{m}_z \sin \hat{\theta} \cos \hat{\phi} \\ \hat{H}_y &= \tilde{m}_y \cos \hat{\phi} - \tilde{m}_z \sin \hat{\phi}\end{aligned}$$

with ψ representing the true value of heading,

$$\begin{aligned}\hat{\phi} &= \phi + \delta\phi \\ \hat{\theta} &= \theta + \delta\theta\end{aligned}$$

representing the estimated roll and pitch angles, and

$$\begin{aligned}\tilde{m}_x &= m_x + n_x \\ \tilde{m}_y &= m_y + n_y \\ \tilde{m}_z &= m_z + n_z\end{aligned}$$

denoting the error contaminated measurements of the 3-axis magnetometer where n_x , n_y , and n_z representing the corresponding measurement noises. n_x , n_y , and n_z can be regarded as white noises.

Using Taylor's expansion, the heading error can be approximated by

$$\delta\psi_m = \frac{\partial\psi}{\partial\theta}\delta\theta + \frac{\partial\psi}{\partial\phi}\delta\phi + \frac{\partial\psi}{\partial m_x}\delta m_x + \frac{\partial\psi}{\partial m_y}\delta m_y + \frac{\partial\psi}{\partial m_z}\delta m_z$$

where it has been assumed that the variation angle ψ_v is accurate and can be regarded as constant.

$$\begin{aligned}
\frac{\partial \psi}{\partial \theta} &= \frac{\partial \left[\arctan \left(\frac{H_y}{H_x} \right) \right]}{\partial \theta} = \frac{1}{1 + \left(\frac{H_y}{H_x} \right)^2} \frac{\frac{\partial H_y}{\partial \theta} H_x - \frac{\partial H_x}{\partial \theta} H_y}{H_x^2} \\
&= \frac{\frac{\partial H_y}{\partial \theta} H_x - \frac{\partial H_x}{\partial \theta} H_y}{H_x^2 + H_y^2} \\
\frac{\partial \psi}{\partial \phi} &= \frac{\partial \left[\arctan \left(\frac{H_y}{H_x} \right) \right]}{\partial \phi} = \frac{\frac{\partial H_y}{\partial \phi} H_x - \frac{\partial H_x}{\partial \phi} H_y}{H_x^2 + H_y^2} \\
\frac{\partial \psi}{\partial m_x} &= \frac{\partial \left[\arctan \left(\frac{H_y}{H_x} \right) \right]}{\partial m_x} = \frac{\frac{\partial H_y}{\partial m_x} H_x - \frac{\partial H_x}{\partial m_x} H_y}{H_x^2 + H_y^2} \\
\frac{\partial \psi}{\partial m_y} &= \frac{\partial \left[\arctan \left(\frac{H_y}{H_x} \right) \right]}{\partial m_y} = \frac{\frac{\partial H_y}{\partial m_y} H_x - \frac{\partial H_x}{\partial m_y} H_y}{H_x^2 + H_y^2} \\
\frac{\partial \psi}{\partial m_z} &= \frac{\partial \left[\arctan \left(\frac{H_y}{H_x} \right) \right]}{\partial m_z} = \frac{\frac{\partial H_y}{\partial m_z} H_x - \frac{\partial H_x}{\partial m_z} H_y}{H_x^2 + H_y^2}
\end{aligned}$$

5

Then the following equations can be derived:

$$\begin{aligned}
\frac{\partial H_x}{\partial \theta} &= \frac{\partial}{\partial \theta} (m_x \cos \theta + m_y \sin \theta \sin \phi + m_z \sin \theta \cos \phi) \\
&= -m_x \sin \theta + m_y \cos \theta \sin \phi + m_z \cos \theta \cos \phi
\end{aligned}$$

$$\begin{aligned}
\frac{\partial H_x}{\partial \phi} &= \frac{\partial}{\partial \phi} (m_x \cos \theta + m_y \sin \theta \sin \phi + m_z \sin \theta \cos \phi) \\
&= m_y \sin \theta \cos \phi - m_z \sin \theta \sin \phi
\end{aligned}$$

$$\frac{\partial H_x}{\partial m_x} = \frac{\partial}{\partial m_x} (m_x \cos \theta + m_y \sin \theta \sin \phi + m_z \sin \theta \cos \phi) = \cos \theta$$

10

$$\frac{\partial H_x}{\partial m_y} = \frac{\partial}{\partial m_y} (m_x \cos \theta + m_y \sin \theta \sin \phi + m_z \sin \theta \cos \phi) = \sin \theta \sin \phi$$

$$\frac{\partial H_x}{\partial m_z} = \frac{\partial}{\partial m_z} (m_x \cos \theta + m_y \sin \theta \sin \phi + m_z \sin \theta \cos \phi) = \sin \theta \cos \phi$$

$$\frac{\partial H_y}{\partial \theta} = \frac{\partial}{\partial \theta} (m_y \cos \phi - m_z \sin \phi) = 0$$

$$\frac{\partial H_y}{\partial \phi} = \frac{\partial}{\partial \phi} (m_y \cos \phi - m_z \sin \phi) = -m_y \sin \phi - m_z \cos \phi$$

$$\frac{\partial H_y}{\partial m_x} = \frac{\partial}{\partial m_x} (m_y \cos \phi - m_z \sin \phi) = 0$$

5

$$\frac{\partial H_y}{\partial m_y} = \frac{\partial}{\partial m_y} (m_y \cos \phi - m_z \sin \phi) = \cos \phi$$

$$\frac{\partial H_y}{\partial m_z} = \frac{\partial}{\partial m_z} (m_y \cos \phi - m_z \sin \phi) = -\sin \phi$$

Therefore, the magnetometer calculated heading error model can be described by

$$\begin{aligned} \delta \psi_m &= \frac{\partial \psi}{\partial \theta} \delta \theta + \frac{\partial \psi}{\partial \phi} \delta \phi + \frac{\partial \psi}{\partial m_x} \delta m_x + \frac{\partial \psi}{\partial m_y} \delta m_y + \frac{\partial \psi}{\partial m_z} \delta m_z \\ &= \frac{\frac{\partial H_y}{\partial \theta} H_x - \frac{\partial H_x}{\partial \theta} H_y}{H_x^2 + H_y^2} \delta \theta + \frac{\frac{\partial H_y}{\partial \phi} H_x - \frac{\partial H_x}{\partial \phi} H_y}{H_x^2 + H_y^2} \delta \phi \\ &\quad + \frac{\frac{\partial H_y}{\partial m_x} H_x - \frac{\partial H_x}{\partial m_x} H_y}{H_x^2 + H_y^2} + \frac{\frac{\partial H_y}{\partial m_y} H_x - \frac{\partial H_x}{\partial m_y} H_y}{H_x^2 + H_y^2} + \frac{\frac{\partial H_y}{\partial m_z} H_x - \frac{\partial H_x}{\partial m_z} H_y}{H_x^2 + H_y^2} \\ &= \frac{\delta \theta}{H_x^2 + H_y^2} (-m_x m_y \sin \theta \cos \phi + m_y^2 \cos \theta \sin \phi \cos \phi + m_y m_z \cos \theta \cos \phi \sin \phi \\ &\quad + m_x m_z \sin \theta \sin \phi - m_y m_z \cos \theta \sin^2 \phi - m_z^2 \cos \theta \sin \phi \cos \phi) \\ &\quad + \frac{\delta \phi}{H_x^2 + H_y^2} [-m_x m_y \cos \theta \sin \phi - m_x m_z \cos \theta \cos \phi - m_y^2 \sin \theta - m_z^2 \sin \theta \\ &\quad + m_y m_z \sin \theta \sin 2\phi] \\ &\quad - \frac{H_y \cos \theta}{H_x^2 + H_y^2} n_x + \frac{H_x \cos \phi - H_y \sin \theta \sin \phi}{H_x^2 + H_y^2} n_y - \frac{H_x \sin \phi + H_y \sin \theta \cos \phi}{H_x^2 + H_y^2} n_z \end{aligned}$$

From $H_z = -m_x \sin \theta + m_y \cos \theta \sin \phi + m_z \cos \theta \cos \phi$, the error model for the vertical magnetic field intensity can be written as

$$\begin{aligned}\delta H_z &= \frac{\partial H_z}{\partial \phi} \delta \phi + \frac{\partial H_z}{\partial \theta} \delta \theta + \frac{\partial H_z}{\partial m_x} \delta m_x + \frac{\partial H_z}{\partial m_y} \delta m_y + \frac{\partial H_z}{\partial m_z} \delta m_z \\ &= (m_y \cos \theta \cos \phi - m_z \cos \theta \sin \phi) \cdot \delta \phi \\ &\quad - (m_x \cos \theta + m_y \sin \theta \sin \phi + m_z \sin \theta \cos \phi) \cdot \delta \theta \\ &\quad - \sin \theta \cdot \delta m_x + \cos \theta \sin \phi \cdot \delta m_y + \cos \theta \cos \phi \cdot \delta m_z\end{aligned}$$

Attitude Estimation by Gyros

5 When using gyro measurements to estimate the attitude information, the attitude can be represented by one of

- a) direction cosine matrix;
- b) Euler angles; and
- c) Quaternion.

10 The direction cosine matrix representation is used hereafter to illustrate the present invention.

Denote the direction cosine matrix from the body coordinate frame to the

horizontal reference frame as $C_b^n = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix}$ and the gyro measurement

vector as $\bar{\omega}_{ib}^b$. Denote the rotation rate of this horizontal reference frame with

15 respect to the inertial frame that is a stationary frame in space expressed in the

horizontal reference frame as $\bar{\omega}_{in}^n$. Then the attitude can be updated using the

following equation:

$$\dot{C}_b^n = C_b^n \Omega_{ib}^b - \Omega_{in}^n C_b^n$$

where Ω_{ib}^b and Ω_{in}^n are the skew symmetric matrices of $\bar{\omega}_{ib}^b$ and $\bar{\omega}_{in}^n$, respectively. The skew symmetric matrix is such defined that

$$\Omega_{ib}^b = \begin{bmatrix} 0 & -\omega_z^b & \omega_y^b \\ \omega_z^b & 0 & -\omega_x^b \\ -\omega_y^b & \omega_x^b & 0 \end{bmatrix}$$

Error Model of Gyros

- 5 When the attitude is expressed by direction cosine matrix C_b^n , the attitude error can be denoted by an error angle vector $\bar{\psi} = [\delta\alpha \ \delta\beta \ \delta\gamma]^T$, such that the estimated direction cosine matrix may be expressed by

$$\tilde{C}_b^n = (I - [\bar{\psi} \times])C_b^n$$

where $[\bar{\psi} \times]$ refers to the skew symmetric matrix of vector $\bar{\psi}$.

- 10 The gyro attitude estimation error model is then given by

$$\dot{\bar{\psi}} = -\bar{\omega}_{in}^n \times \bar{\psi} - C_b^n \delta\bar{\omega}_{ib}^b$$

where $\delta\bar{\omega}_{ib}^b$ denotes the gyro measurement error vector.

Relationship between $\bar{\psi}$ and Euler Angle Errors

- 15 To integrate the magnetometer and gyro information, it is essential to find the relationship between the Euler angle error vector $[\delta\phi \ \delta\theta \ \delta\psi]^T$ and the vector $\bar{\psi}$. Note that the two angle vectors are different. In fact, expressing the direction cosine matrix in terms of Euler angles, we have

$$\begin{aligned} C_b^n &= \begin{bmatrix} \cos\theta \cos\psi & -\cos\phi \sin\psi + \sin\phi \sin\theta \cos\psi & \sin\phi \sin\psi + \cos\phi \sin\theta \cos\psi \\ \cos\theta \sin\psi & \cos\phi \cos\psi + \sin\phi \sin\theta \sin\psi & -\sin\phi \cos\psi + \cos\phi \sin\theta \sin\psi \\ -\sin\theta & \sin\phi \cos\theta & \cos\phi \cos\theta \end{bmatrix} \\ &= f(\phi, \theta, \psi) \end{aligned}$$

- 20 and the estimated direction cosine matrix may be written as

$$\begin{aligned}
\tilde{C}_b^n &= f(\tilde{\phi}, \tilde{\theta}, \tilde{\psi}) \\
&= \begin{bmatrix} \cos \tilde{\theta} \cos \tilde{\psi} & -\cos \tilde{\phi} \sin \tilde{\psi} + \sin \tilde{\phi} \sin \tilde{\theta} \cos \tilde{\psi} & \sin \tilde{\phi} \sin \tilde{\psi} + \cos \tilde{\phi} \sin \tilde{\theta} \cos \tilde{\psi} \\ \cos \tilde{\theta} \sin \tilde{\psi} & \cos \tilde{\phi} \cos \tilde{\psi} + \sin \tilde{\phi} \sin \tilde{\theta} \sin \tilde{\psi} & -\sin \tilde{\phi} \cos \tilde{\psi} + \cos \tilde{\phi} \sin \tilde{\theta} \sin \tilde{\psi} \\ -\sin \tilde{\theta} & \sin \tilde{\phi} \cos \tilde{\theta} & \cos \tilde{\phi} \cos \tilde{\theta} \end{bmatrix} \\
&= \begin{bmatrix} \tilde{c}_{11} & \tilde{c}_{12} & \tilde{c}_{13} \\ \tilde{c}_{21} & \tilde{c}_{22} & \tilde{c}_{23} \\ \tilde{c}_{31} & \tilde{c}_{32} & \tilde{c}_{33} \end{bmatrix}
\end{aligned}$$

The estimated Euler angles may be derived by

$$\begin{aligned}
\hat{\phi} &= \arctan\left(\frac{\tilde{c}_{32}}{\tilde{c}_{33}}\right) \\
\hat{\theta} &= -\arcsin(\tilde{c}_{31}) \\
\hat{\psi} &= \arctan\left(\frac{\tilde{c}_{21}}{\tilde{c}_{11}}\right)
\end{aligned}$$

5 From $\tilde{C}_b^n = (I - \bar{\psi} \times) C_b^n = \begin{bmatrix} 1 & \delta\gamma & -\delta\beta \\ -\delta\gamma & 1 & \delta\alpha \\ \delta\beta & -\delta\alpha & 1 \end{bmatrix} \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix}$ it can be

derived that

$$\begin{aligned}
\tilde{c}_{11} &= c_{11} - c_{31}\delta\beta + c_{21}\delta\gamma \\
\tilde{c}_{21} &= c_{21} + c_{31}\delta\alpha - c_{11}\delta\gamma \\
\tilde{c}_{31} &= c_{31} - c_{21}\delta\alpha + c_{11}\delta\beta \\
\tilde{c}_{32} &= c_{32} - c_{22}\delta\alpha + c_{12}\delta\beta \\
\tilde{c}_{33} &= c_{33} - c_{23}\delta\alpha + c_{13}\delta\beta
\end{aligned}$$

The relationship between the Euler angle errors and the error angle vector $\bar{\psi}$ is derived below:

$$\begin{aligned}
\hat{\psi} &= \arctan\left(\frac{\tilde{c}_{21}}{\tilde{c}_{11}}\right) = \arctan\left(\frac{c_{21} + c_{31}\delta\alpha - c_{11}\delta\gamma}{c_{11} - c_{31}\delta\beta + c_{21}\delta\gamma}\right) \\
&= \psi + \delta\psi = \arctan\left(\frac{c_{21}}{c_{11}}\right) + \delta\psi
\end{aligned}$$

Introduce the symbol δt such that

$$\delta t = \frac{c_{21} + c_{31}\delta\alpha - c_{11}\delta\gamma}{c_{11} - c_{31}\delta\beta + c_{21}\delta\gamma} - \frac{c_{21}}{c_{11}} = \frac{c_{11}c_{31}\delta\alpha + c_{21}c_{31}\delta\beta - (c_{11}^2 + c_{21}^2)\delta\gamma}{c_{11}(c_{11} - c_{31}\delta\beta + c_{21}\delta\gamma)}$$

Then, equation (1) can be written as

$$\begin{aligned}\hat{\psi} &= \arctan\left(\frac{\tilde{c}_{21}}{\tilde{c}_{11}}\right) = \arctan\left(\frac{c_{21} + c_{31}\delta\alpha - c_{11}\delta\gamma}{c_{11} - c_{31}\delta\beta + c_{21}\delta\gamma}\right) \\ &= \psi + \delta\psi = \arctan\left(\frac{c_{21}}{c_{11}} + \delta t\right) \\ &\approx \arctan\left(\frac{c_{21}}{c_{11}}\right) + \frac{\partial}{\partial x} \arctan(x) \Big|_{x=\frac{c_{21}}{c_{11}}} \cdot \delta t \\ &= \psi + \frac{1}{1 + \left(\frac{c_{21}}{c_{11}}\right)^2} \delta t\end{aligned}$$

5 Therefore, we have

$$\delta\psi = \frac{1}{1 + \left(\frac{c_{21}}{c_{11}}\right)^2} \delta t = \frac{1}{1 + \left(\frac{c_{21}}{c_{11}}\right)^2} \cdot \frac{c_{11}c_{31}\delta\alpha + c_{21}c_{31}\delta\beta - (c_{11}^2 + c_{21}^2)\delta\gamma}{c_{11}(c_{11} - c_{31}\delta\beta + c_{21}\delta\gamma)}$$

Assume that $\delta\alpha$, $\delta\beta$, and $\delta\gamma$ are small angles, the above equation can be approximated by

$$\begin{aligned}\delta\psi &= \frac{1}{1 + \left(\frac{c_{21}}{c_{11}}\right)^2} \delta t \approx \frac{1}{1 + \left(\frac{c_{21}}{c_{11}}\right)^2} \cdot \frac{c_{11}c_{31}\delta\alpha + c_{21}c_{31}\delta\beta - (c_{11}^2 + c_{21}^2)\delta\gamma}{c_{11}^2} \\ &= \frac{c_{11}c_{31}}{c_{11}^2 + c_{21}^2} \delta\alpha + \frac{c_{21}c_{31}}{c_{11}^2 + c_{21}^2} \delta\beta - \delta\gamma\end{aligned}$$

10 The relationship between the pitch estimate $\hat{\theta} = -\arcsin(\tilde{c}_{31})$ and $\bar{\psi}$ are derived below.

$$\begin{aligned}\hat{\theta} &= -\arcsin(\tilde{c}_{31}) = \theta + \delta\theta = -\arcsin(c_{31} - c_{21}\delta\alpha + c_{11}\delta\beta) \\ &= -\arcsin(c_{31} + \delta t)\end{aligned}$$

where

$$\delta t = -c_{21}\delta\alpha + c_{11}\delta\beta$$

The pitch angle estimate can be further expressed as

$$\begin{aligned}\hat{\theta} &= \theta + \delta\theta = -\arcsin(c_{31}) - \frac{\partial}{\partial x}\arcsin(x)\Big|_{x=c_{31}} \cdot \delta t \\ 5 \quad &= \theta - \frac{1}{\sqrt{1-x^2}}\Big|_{x=c_{31}} \cdot \delta t \\ &= \theta - \frac{1}{\sqrt{1-c_{31}^2}} \cdot (-c_{21}\delta\alpha + c_{11}\delta\beta)\end{aligned}$$

Therefore, we have

$$\begin{aligned}\delta\theta &= -\frac{1}{\sqrt{1-c_{31}^2}} \cdot (-c_{21}\delta\alpha + c_{11}\delta\beta) \\ &= \frac{c_{21}}{\sqrt{1-c_{31}^2}}\delta\alpha - \frac{c_{11}}{\sqrt{1-c_{31}^2}}\delta\beta\end{aligned}$$

The relationship between the roll angle estimate $\hat{\phi} = \arctan\left(\frac{\tilde{c}_{32}}{\tilde{c}_{33}}\right)$ and $\bar{\psi}$ is derived below.

$$\begin{aligned}\hat{\phi} &= \phi + \delta\phi = \arctan\left(\frac{\tilde{c}_{32}}{\tilde{c}_{33}}\right) = \arctan\left(\frac{c_{32} - c_{22}\delta\alpha + c_{12}\delta\beta}{c_{33} - c_{23}\delta\alpha + c_{13}\delta\beta}\right) \\ 10 \quad &= \arctan\left(\frac{c_{32}}{c_{33}} + \delta t\right)\end{aligned}$$

where

$$\delta t = \frac{c_{32} - c_{22}\delta\alpha + c_{12}\delta\beta}{c_{33} - c_{23}\delta\alpha + c_{13}\delta\beta} - \frac{c_{32}}{c_{33}} = \frac{(c_{23}c_{32} - c_{22}c_{33})\delta\alpha + (c_{12}c_{33} - c_{13}c_{32})\delta\beta}{c_{33}(c_{33} - c_{23}\delta\alpha + c_{13}\delta\beta)}.$$

Similar to the derivation of the relationship between $\delta\psi$ and $\bar{\psi}$, the relationship between $\delta\phi$ and $\bar{\psi}$ is given as below:

$$\delta\phi = \frac{c_{23}c_{32} - c_{22}c_{33}}{c_{32}^2 + c_{33}^2} \delta\alpha + \frac{c_{12}c_{33} - c_{13}c_{32}}{c_{32}^2 + c_{33}^2} \delta\beta$$

5 The matrix form of the relationship between Euler angle errors and $\bar{\psi}$ is given by

$$\begin{bmatrix} \delta\phi \\ \delta\theta \\ \delta\psi \end{bmatrix} = \begin{bmatrix} \frac{c_{23}c_{32} - c_{22}c_{33}}{c_{32}^2 + c_{33}^2} & \frac{c_{12}c_{33} - c_{13}c_{32}}{c_{32}^2 + c_{33}^2} & 0 \\ \frac{c_{21}}{\sqrt{1 - c_{31}^2}} & -\frac{c_{11}}{\sqrt{1 - c_{31}^2}} & 0 \\ \frac{c_{11}c_{31}}{c_{11}^2 + c_{21}^2} & \frac{c_{21}c_{31}}{c_{11}^2 + c_{21}^2} & -1 \end{bmatrix} \begin{bmatrix} \delta\alpha \\ \delta\beta \\ \delta\gamma \end{bmatrix} = C_{Euler}^{\bar{\psi}} \bar{\psi}$$

Having provided the relevant background, particular embodiments of the invention may now be described in sufficient detail to enable a person of average skill in the art to perform the invention.

10 With particular reference to figure 1, a gyro signal processing module 11, which uses the 3-axis gyro measurements of a gyroscope measurement module 10 (which may comprise one or more individual gyroscopes) to generate its relative rotation angles with respect to the reference frame, $\hat{\phi}, \hat{\theta}, \hat{\psi}$, with $\hat{\phi}$ representing the roll angle estimate, $\hat{\theta}$ the pitch angle estimate, and $\hat{\psi}$ the yaw angle estimate.

A magnetic signal processing module 21, which uses the magnetic measurements from the 3-axis magnetometer 20 and the pitch and roll angles generated by the gyro signal processing module 11 to calculate the yaw angle $\hat{\psi}_m$ and the vertical magnetic field intensity $\hat{H}_{zm}$.

A sensor fusion filter 40, which may be a Kalman filter, or information filter, estimates the errors in the rotation angles generated by the gyro signal processing module 11 to compensate the system output, and can also estimate the gyro drift, scale factors, as well as other gyro error parameters for sensor measurement calibration. The dynamic model for the sensor fusion filter may comprise a state-space equation and a measurement equation. The state-space equation may be based on the gyro error model where the state vector comprises at least a roll angle error, a pitch angle error, a heading angle error and it may further contain error parameters of gyro measurements. The measurement equation may be based on the magnetometer error model where the measurement vector comprises two elements: one is the difference between the gyro estimated heading and the magnetometer calculated heading, and the other is the difference between the estimated true vertical magnetic field intensity and the estimated vertical magnetic field intensity generated by the magnetic signal processing module 21.

An initialization module 30, which provides the initial attitude of the system to the gyro signal processing module 11, the initial states and covariance matrix to the sensor fusion filter 40, and the estimated true value of the vertical magnetic field intensity, H_{z0} , to compare with the vertical magnetic field intensity generated by the magnetic signal processing module 21, $\hat{H}_{zm}$.

In the sensor fusion filter 40, usually an (extended) Kalman filter or an information filter, besides angular errors, the states can also include gyro error parameters such as drifts, scale factors, and so on, and some magnetic sensors compensation parameters. Once the sensor fusion filter 40 has estimated these parameters, they can be used to compensate or calibrate the gyro and magnetic sensors.

Using the feature of involving the vertical magnetic field estimate, will improve the accuracy of the rotation angle estimates.

With reference to Figure 2 a block diagram of one embodiment of the

present 3-dimensional attitude apparatus is shown incorporating the modules shown in figure 1.

The overall apparatus 100 of figure 2 can be roughly divided into the following modules:

5 A Gyro sensor module 210, which generates raw angular rate measurements. The gyros may be either analog or digital sensors.

A Magnetic sensor module 220, which generate 3-dimensional magnetic measurements of the earth's magnetic field. It also may be comprised of either analog or digital components.

10 A gyro pre-processing module 211, which contains the circuits if necessary to pre-process the raw gyro measurements. For example, if the gyros are analog gyros, the gyro pre-processing module 211 may contain amplifiers, filters, A/D converters to transform the gyro raw signals to a digital signal.

A magnetic signal pre-processing module 221, which transforms the raw
15 measurements of the magnetic sensor module 220 if necessary to a signal appropriate for the subsequent processing.

An initialization sensor module 200, which contains some sensors and circuits to generate necessary information for the processor to implement initialization for the gyro attitude computation module and the sensor fusion filter
20 40. Initialization is to estimate the initial attitude of the system before normal operation. Different applications may use different initialization methods. For example, in some applications, the system may always be leveling at the beginning. In such cases, no external sensors are needed. In that case, the initialization is realized by assuming that the pitch and roll angles are zero, and
25 the yaw angle is obtained through the magnetic sensors. In other circumstances, other sensors are used to obtain the initial pitch and roll angles. Fortunately, in most applications, the system is initially stationary or moving slowly. Then tilt sensors may be used to obtain the initial pitch and roll. The tilt sensors may be electrolyte tilt sensors or accelerometers. The initial module may even be a user

interface module for the user or external systems to transmit the initial attitudes to this attitude apparatus.

A processor 230 to calculate the gyro generated attitude angle estimates, the magnetic heading, the vertical magnetic field intensity, to implement the
5 sensor combination algorithms 50 as shown in figure 1, and to generate the estimated 3-dimensional attitude information.

A user interface module 203, which comprises appropriate circuits and hardware interfaces to ensure users are able to access the attitude output conveniently.

10 A power module 201, which provides appropriate power supplies to each sensor, circuit, and processor.

A clock module 202, which provides necessary time references to the sensors, processor, and the user interface module.

The embodiment shown in figure 2 of the apparatus is simple to fabricate.
15 If using MEMS gyros, a compact, accurate, while low cost embedded 3-dimensional attitude sensor may be developed for a wide range of applications. The following is a non-exhaustive list of applications, whether the invention is fabricated, preferably, in MEMS form or otherwise:

- 20 1. Navigation systems such as those for airplanes, unmanned aerial vehicles, land vehicles, robots, ships, underwater vehicles, and other navigation systems that need to generate attitude information of the carriers.
2. Virtual reality systems where the 3-dimensional attitude information of the human being or other objects is needed.
- 25 3. Autonomous aiming systems for various artillery systems.
4. Autonomous aiming systems for onboard cameras.

In the above descriptions of the present invention, the heading is referred to with respect to magnetic north. If the heading is required to be with respect to true north, or geographic north, then an additional Magnetic Field Variation Angle

Generator module may be added to provide the magnetic field variation angle. This module may comprise either a geomagnetic declination map, or a GPS receiver and an IGRF model (International Geomagnetic Reference Field). Two different approaches are shown in Figure 3 and Figure 4, respectively.

5 All modules shown in Figures 3 and 4 are given reference numerals corresponding to the modules of Figure 1, which have an identical function and with the addition of a prefix numeral 3, and a prefix numeral 4 in each of Figures 3 and 4, respectively.

10 In Figure 3, the output of the Magnetic Field Variation Angle Generator module 360 is fed into the Magnetic Signal Processing module 321 so that the Magnetic Signal Processing module 321 may output a heading estimate with respect to true north. The initial heading estimate from the Initialization module 330 is also with respect to true north.

15 In Figure 4, the heading estimates in all the other modules are with respect to magnetic north, and the output of the Magnetic Field Variation Angle Generator module 460 is used to correct the heading estimate after the sensor fusion process.

20 While this invention has been described in connection with specific embodiments thereof, it will be understood that it is capable of further modification(s). This application is intended to cover any variations, uses or adaptations of the invention following in general, the principles of the invention and including such departures from the present disclosure as come within known or customary practice within the art to which the invention pertains and as may be applied to the essential features hereinbefore set forth.

25 As the present invention may be embodied in several forms without departing from the spirit of the essential characteristics of the invention, it should be understood that the above described embodiments are not to limit the present invention unless otherwise specified, but rather should be construed broadly within the spirit and scope of the invention as defined in the appended claims.

Various modifications and equivalent arrangements are intended to be included within the spirit and scope of the invention and appended claims. Therefore, the specific embodiments are to be understood to be illustrative of the many ways in which the principles of the present invention may be practiced. In the following

5 claims, means-plus-function clauses are intended to cover structures as performing the defined function and not only structural equivalents, but also equivalent structures. For example, although a nail and a screw may not be structural equivalents in that a nail employs a cylindrical surface to secure wooden parts together, whereas a screw employs a helical surface to secure

10 wooden parts together, in the environment of fastening wooden parts, a nail and a screw are equivalent structures.

“Comprises/comprising” when used in this specification is taken to specify the presence of stated features, integers, steps or components but does not preclude the presence or addition of one or more other features, integers, steps,

15 components or groups thereof.”

CLAIMS

1. A method of determining an estimate of attitude with respect to a fixed reference frame, the method comprising the steps of:

generating angle estimates comprising at least a pitch angle estimate, a
5 roll angle estimate and a yaw angle estimate from measurements of a gyroscopic sensor means;

calculating a heading estimate from data comprising measurements of a magnetic sensor means and the pitch and roll angle estimates generated by the gyroscopic sensor means, and;

10 estimating signal parameters of the generated angle estimates from data comprising:

a) a difference of the calculated heading estimate based on the measurements of the magnetic sensor means and the heading estimate based on the measurements of the gyroscopic sensor means, and;

15 b) a difference of an estimate of the vertical magnetic field intensity based on measurements of the magnetic sensor means and an estimated true vertical magnetic field intensity

2. A method as claimed in claim 1 wherein the estimated true vertical
20 magnetic field intensity is derived from an initialization module.

3. A method as claimed in claim 1 or 2 wherein the step of estimating further comprises estimating signal parameters of the calculated heading estimate.

25

4. A method as claimed in any one of claims 1 to 3 further comprising the step of compensating one or more of:

a) the generated angle estimates and;

b) the calculated heading estimate

with the estimated signal parameters.

5. A method as claimed in any one of claims 1 to 4 wherein the estimated signal parameters comprise error parameter estimates of the measurements from the gyroscopic sensor means and the magnetic sensor means.

6. A method as claimed in any one of claims 1 to 5 wherein the generated angle estimates comprise a roll angle estimate, a pitch angle estimate and a yaw angle estimate.

7. A method as claimed in any one of claims 1 to 6 wherein the calculated heading estimate comprises a calculated yaw angle based on the measurements from the magnetic sensor means.

8. A method as claimed in any one of claims 1 to 7 wherein the step of estimating comprises performing one of:

a) a Kalman filter operation and;

b) an information filter operation;

on a numerical difference signal of the calculated heading estimate based on the measurements from the magnetic sensor means and the generated heading estimate based on the measurements from the gyroscopic sensor means.

9. A method as claimed in any one of claims 1 to 8 wherein the calculated heading estimate comprises one or more of an azimuth estimate, and a yaw angle estimate.

10. Apparatus adapted to determine an estimate of attitude with respect to a fixed reference frame, said apparatus including:

processor means adapted to operate in accordance with a predetermined instruction set,

5 said apparatus, in conjunction with said instruction set, being adapted to perform the method as claimed in any one of claims 1 to 8.

11. Apparatus as claimed in claim 10 wherein the gyroscopic means comprises a 3-axis gyroscope.

10

12. Apparatus as claimed in claim 10 or 11 wherein the magnetic sensor means comprises a 3-axis magnetometer.

13. Apparatus as claimed in any one of claims 10 to 12 comprising one
15 of:

- a) a Kalman filter and;
 - b) an information filter
- for estimating the signal parameters.

20 14. A computer program product including:
a computer usable medium having computer readable program code and computer readable system code embodied on said medium for determining an estimate of attitude with respect to a fixed reference frame within a data processing system, said computer program product including:

25 computer readable code within said computer usable medium for performing the method of any one of claims 1 to 9.

14. A method as herein described.

15. An apparatus as herein described.